EXPERIMENTAL ANALYSIS OF JET FIRE IMPINGEMENT ON INDUSTRIAL PIPE

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INTRODUCTION

In industrial plants, jet fires and pool fires can increase hazards when they impinge and engulf on pipes or vessels. Then, these structures may also become themselves the centre of major accidents (domino effects).

Therefore, as part of hazard surveys and more particularly survey of domino effects, some questions are asked about, for example:

- the relevance to consider the explosion of such or such tank as a result of the contribution of heat since a close fire considered besides,
- or again the quantitative contribution expected by the implementation of materials of heat insulation or the implementation of means of cooling.

Thus a research program supported by the French Ministry for Ecology and Sustainable Development focuses on the thermal impact of fires on industrial pipes and tanks. Its main objective is to develop, to validate and to produce one or several tools of calculation satisfying needs mentioned above.

This paper presents an experimental campaign aiming to the analysis of the heat transfers exerting on a pipe impinged by a jet fire. Thus, an experimental apparatus was set up making it possible to determine on the one hand, precisely the characteristics of jet fire and on the other hand, the thermal response of the steel pipe crossed by water flow.

First of all, to characterise jet fire, measurements of gas temperatures, gas velocities and heat fluxes are performed for three gases that are the methane, propane and ethylene and for various gas release rates. Additionally, test monitoring has also been done with video camera. These measurements make it possible to define dimensions of jet fires, its surface emissive power as well as the hot gas velocities for finally deducing the heat transfers received by the pipe. The experimental data are compared with the SHELL model which is a semi-empirical model (Chamberlain, 1987) modified by Cook (1987).

In the second time, the pipe crossed by cold water is subjected to these various jet fires and the thermal response of pipe is quantified by monitoring the pipe with thermocouples. This second test campaign aims to quantify the influence of the hot soot conduction in the heat transfers.

EXPERIMENTAL APPARATUS

A first experimental campaign consisted in determining precisely the characteristics of jet fire and a second campaign made it possible to define the thermal response of the pipe impinged by a jet fire. Figure 1 presents a sketch of the global experimental apparatus. The experimental campaigns were realised within the closed INERIS fire gallery that provides a confined medium. Thus, there is no influence of meteorological conditions such as wind.

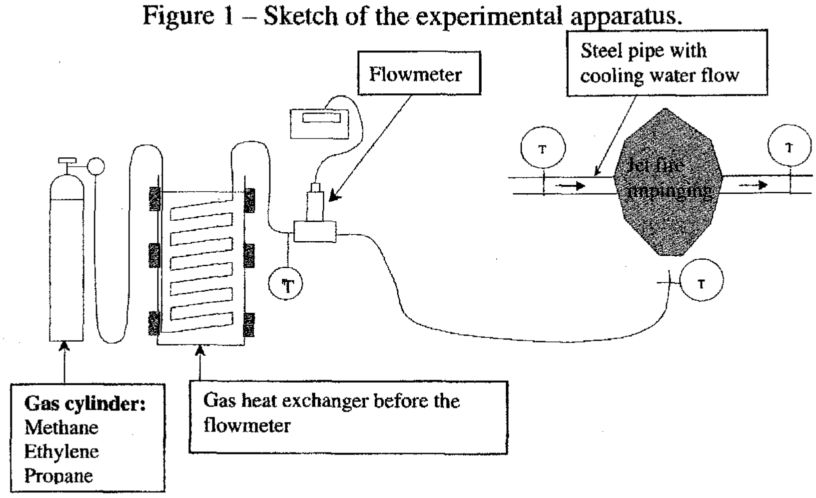
An experimental apparatus was set up making it possible to characterise initially the phenomenon of jet fire for three various gases chosen for their different propensity to produce soot which are methane, propane and ethylene. Figure 1 presents this apparatus which is made up of a gas cylinder and a gas heat exchanger to allow the flowmeter to work in its range of operation. This flowmeter is used to control the exit gas velocity (nozzle diameter d_j being unchanged during all the tests) in order to obtain a jet fire in stationary regime.

A mass flow rate and an exit temperature define the gas jet. Then, in order to characterise jet fire in term of geometry (lift off, flame length...) but also radiative power, various instruments of measurements are used such as:

- thermocouples placed in the axis of the jet fire to measure the hot gas temperatures T_g along the flame,

- an anemometric bi-directional probe moving along the axis of the flame to measure the hot gases velocity U_g,
- radiative fluxmeters located on the sides and above the flame measuring the radiative flux,
- a video camera system to measure dimensions of the flame (by visualisation).

Figure 1 – Sketch of the experimental apparatus.



The plan of tests is presented in Table 1 which indicates for all gases, the ranges of the gas mass flow rate $\dot{m}_f$, of the heat release rate $\dot{Q}$, of the exit gas velocity U_j, of the Reynolds number Re_s, of the Froude number Fr and the effective diameter of the jet D_s. The Froude number is often considered to define the characteristics of jet fire.

Table 1 – Characteristics of jet fires tests.

Gas	$\dot{m}_f$ (g/s)	$\dot{Q}$ (kW)	U_j (m/s)	D_s[1] (mm)	$Re_s = \frac{U_j D_s}{\nu_f}$ (-)	$Fr = \frac{U_j^2}{g D_s}$ (-)
Methane (CH_4) f_s[2] = 18,9 %	1,02 - 3,81	51 - 191	25 - 93	6,6	10000 - 37330	9600 - 134030
Propane (C_3H_8) f_s = 17,6 %	1,23 - 5,31	62 - 296	11 - 47	10,9	27150 - 117200	1130 - 21060
Ethylene (C_2H_4) f_s = 17 %	1,32 - 6,27	57 - 246	18 - 87	8,7	18790 - 89260	3970 - 89530

For the second experimental campaign, the steel pipe is subjected to these various jet fires and the thermal response of pipe is quantified by monitoring the pipe response with thermocouples (Figure 2). It should be noted that measurements are done on the part of the pipe directly impinged by jet fire and symmetrically on the part located in the drag of the flame. The pipe has the following characteristics: internal diameter 22 mm and external diameter 34 mm. The installation is made of three sections of measurements, the section B located in the axis of jet fire, section A 10 cm upstream and section C 10 cm downstream. The thermocouples directly impacted by jet fire are noted AX1, AX2, BX1, BX2, CY3 and CY4 and those in drag noted AY3, AY4, BY3, BY4, CX1 and CX2 (Figure 2). In addition, a collector was also necessary to place the whole of the connectors, and also to ensure the clearing of the extension cables towards outside (Figure 2).
An internal fluid that is water at ambient temperature flows in the pipe. This water flow can be modulated until obtaining a maximum mass flow rate of 12 kg/min. The water temperature is measured using thermocouples upstream and downstream from the sections of measurements.

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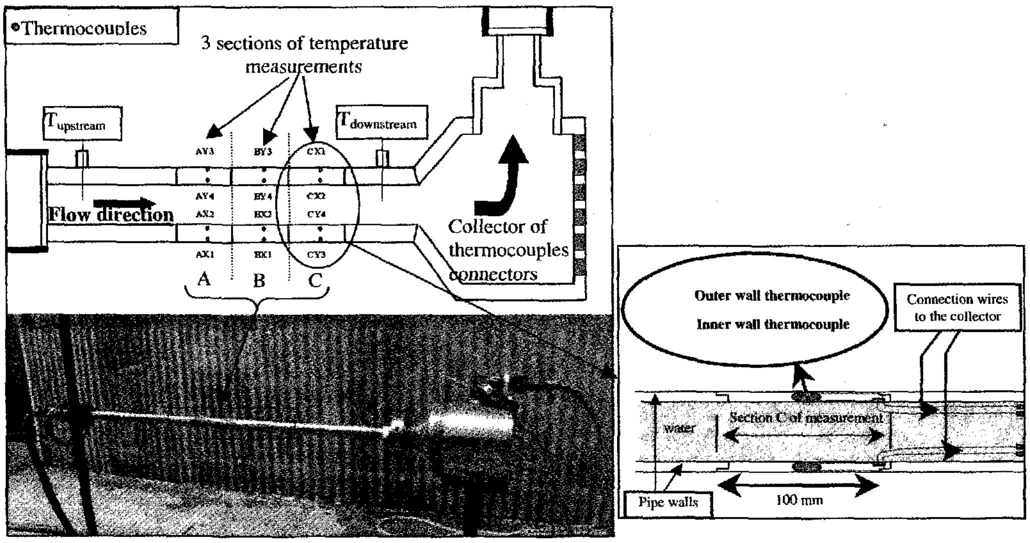
[1] D_s : Effective diameter of the gas jet such as : $D_S = d_j \sqrt{\frac{\rho_{fuel}}{\rho_{air}}}$

[2] f_s : Fraction which represents the fuel mass fraction at which carbon particles begin to form (Beyler, 2002).

Measurements are done with a rate of 2 seconds acquisition and make it possible to obtain an evolution of the steel pipe temperatures. The variable parameters are as follows:

- the jet fire (various gases and the variation of heat release rate),
- the water flow within the pipe (water velocity going from 0 to 0,5 m/s).

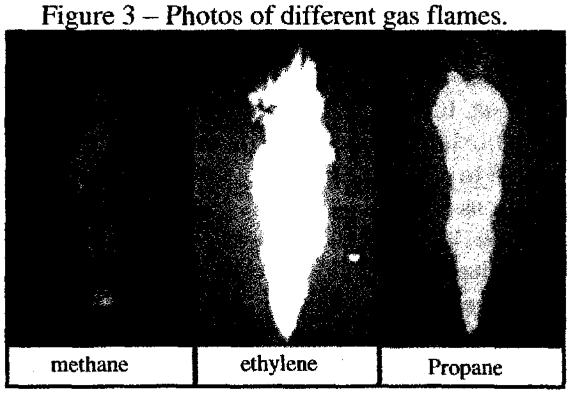
Figure 2 – Sketches and picture of the steel pipe monitored with thermocouples and the collector of connectors.



STRUCTURE OF FLAME

Whatever the gas tested, the visualisation by video camera shows that jet fire takes a general shape of cone (Figure 3) which characterises fully turbulent jet flames whose the Reynolds number is greater than 2000 (Table 1). But the structure of flame differs according to gas. Indeed, the methane flame compared to the propane and ethylene flames has a blue aspect and is very lifted off from the nozzle. The blue color of this flame is characteristic of the radiation in the field of visible of the carbon dioxide and the water vapor. The methane flame is generally considered as a nonluminous flame and soot radiation can be neglected (Marracino, 1997). The soot production in a methane flame is very weak even null under our conditions of tests. At the opposite, the propane and ethylene flames known as luminous are characterised by their yellow color because of their important soot concentration. Indeed, the ethylene and propane have a greater propensity to produce soot (see the f_s fraction in Table 1).

Figure 3 – Photos of different gas flames.



Moreover, the temperature measurements on the axis of jet fire also shows a difference between methane and the two other gases, ethylene and propane. Indeed, at the flame tip, the temperatures are included between 500 and 600 °C for jet fires of ethylene and propane, whereas for methane, they are rather of 900 °C. The temperature range of 500-600 °C corresponds to the empirical criterion given by Mac Caffrey (1979) to define the average flame. Physically, this criterion is explained by considering the spectral distribution of the emissive power of the black body (Planck's law). For the ethylene and propane flames, the radiation is emitted in the field of visible by the soot particles comparable with black bodies. The Planck's law shows that the black body emits radiation in the short range wavelengths of the field of visible (0,4 - 0,8 µm) only when it reaches temperatures higher than 500-600 °C. Below this limit, the black body does not emit any more but in the infra-red one. No radiation is received coming from the soot particles below 500 °C. Consequently, it is coherent that this criterion does not apply to jet fire of methane because the structure is different, the steam and CO2 being the only radiant bodies (semi-transparent bodies) in this flame.

RADIANT ENERGY OF FLAME

The fraction of combustion energy radiated η_r is important in the calculation of the radiative flux received by a target. To estimate it in experiments, a calculation is carried out while being based on the values of radiative flux given by the fluxmeters.

Figures 4 and 5 show the comparison between experiment and SHELL model for the fraction of combustion energy radiated η_r and for the radiative power $\dot{Q}_r$ ($\dot{Q}_r = \eta_r \dot{Q}$) according to the Froude number Fr.

Figure 4: Fraction of combustion energy radiated η_r

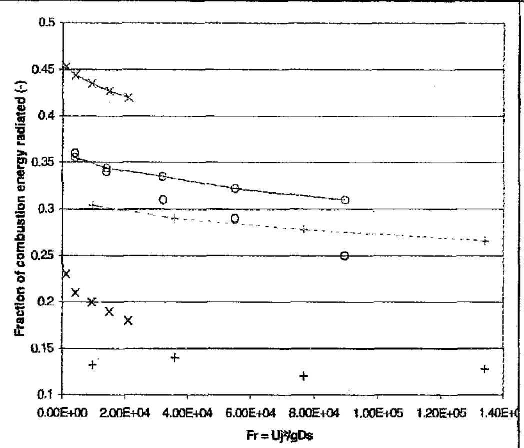
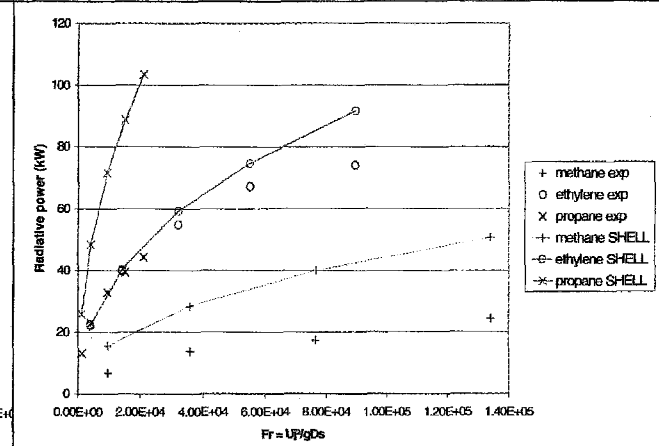


Figure 5: Radiative power $\dot{Q}_r$.



In a general way, the experimental and modelling radiative fractions tend to decrease when the gas jet velocity increases. This observation is a characteristic of the turbulent jet fires rather controlled by the forced convection induced by the gas jet. Even if the fraction of combustion energy radiated η_r is reduced, the radiative power $\dot{Q}_r$ increases with the exit gas velocity. Indeed, the more the mass flow rate grows and the more the flame is going to radiate (Figure 5).

In addition, the radiative fraction of the methane flame is systematically lower than the radiative fractions of propane and ethylene. Indeed, the radiation of a methane jet fire comes exclusively from the water vapor and carbon dioxide which are bodies known as being "semi-transparent". Their emission is very weak compared to the emission of a black body. Conversely, ethylene and propane jet fires have important concentrations of soot, particles radiating as black bodies.

In addition, except for ethylene, the SHELL model (modified by Cook (1987)) gives values of radiative fraction which are at least the double of the experimental values. For a given surface of flame, this would imply a radiative flux received at a given distance multiplied by two.

Moreover, the SHELL model estimates that jet fires of propane have a highest radiative fraction than those of ethylene whereas the tests showed the opposite. Indeed, the calculation is based on the molecular weight of the gas: more it is important and more the gas will have a high radiative fraction. The radiation of the propane and ethylene flames is due mainly to their consequent soot concentration. The alkenes (ethylene) have a greater disposition to produce soot than the alkanes (propane) (Rasbah, 1982). The more the flames are concentrated of soot and the more they tend to radiate until they are saturated with particles. It is completely logical to obtain experimentally a radiative fraction of propane flame weaker than the ethylene one.

Consequently, the calculation of the radiative fraction instead of being based on the molecular weight should rather be a function of the propensity of the gas to form soot. An analysis carried out by Delichatsios (1992) and based on the smoke-point heat release rate $\dot{Q}_{sp}$ [3] allows to define the radiative fraction for jet fires whose radiation is induced mainly by soot. In this model, Delichatsios defines a maximum radiative fraction $\eta_{r\,\max}$ corresponding in a jet fire saturated with soot. Moreover, it defines the radiative fraction as a function of the modified Froude number Fr_f, the smoke-point heat release rate $\dot{Q}_{sp}$ and the gas mass flow rate $\dot{m}_f$ such as:

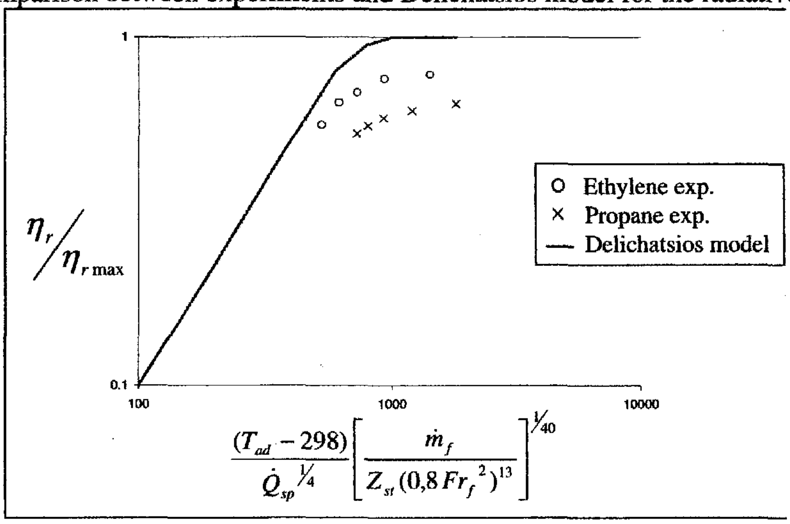
$$\frac{\eta_r}{\eta_{r\,\max}} = fcn\left[\frac{(T_{ad}-298)}{\dot{Q}_{sp}^{1/4}}\left[\frac{\dot{m}_f}{Z_{st}(0{,}8\,Fr_f^{\,2})^{13}}\right]^{1/40}\right] \qquad [1]$$

where: $$Fr_f = \frac{U_j Z_{st}^{1.5}}{\left[\left(\frac{T_{ad}-T_\infty}{T_\infty}\right) g d_j\right]^{0.5}\left(\frac{\rho_{fuel}}{\rho_{air}}\right)^{0.25}}$$

T_{ad} : Adiabatic flame temperature (K),
Z_{st} : stoichiometric ratio (-).

Figure 6 presents a comparison of the experimental and modelling results. On the one hand, the evolution of the radiative fractions obtained in experiments is in adequacy with the Delichatsios model. On the other hand, a variation remains between the experimental and modelling results. This difference is due to the taking into account in the model of a measured adiabatic temperature and non theoretical flame (for ethylene, 2370 K instead of 2637 K).

Figure 6: Comparison between experiments and Delichatsios model for the radiative fraction.



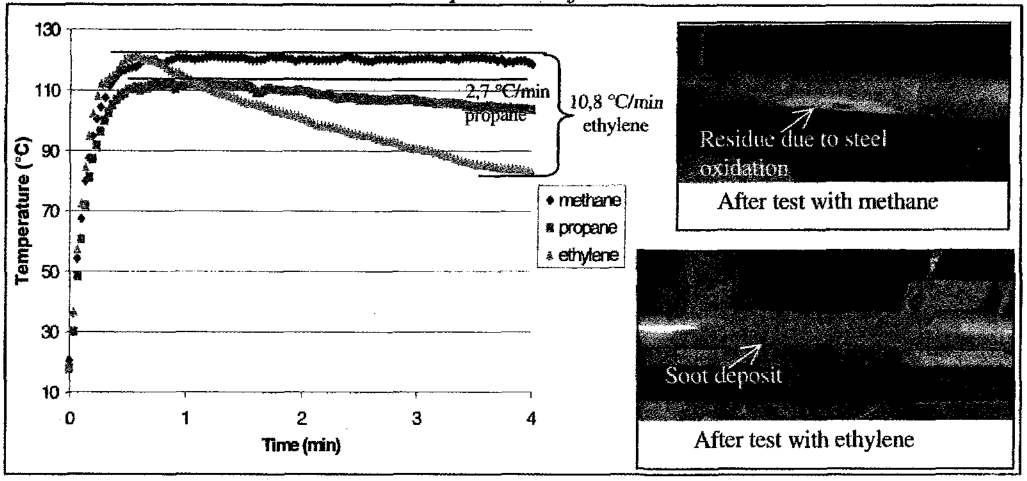
EFFECT OF SOOT ON HEAT TRANSFERS TO THE PIPE

The first tests realised with jet fires showed the differences existing between tested gases in term of soot concentrations. The second experimental campaign based on the jet fire impingement of the steel pipe was performed to apprehend how jet fire interacts with the engulfed equipment.

With this intention, Figure 7 presents the thermal response of the pipe impinged by the flames of three gases (methane, propane and ethylene). The pipe is located at the centre of jet fire and has a water flow of 12 kg/min. The methane mass flow rate is 3,81 g/s, the propane one is 4,48 g/s and the ethylene one is 2,48 g/s (Froude number is the same for propane and ethylene).

[3] The "smoke-point" is a minimum heat release rate at which smoke just escapes from the flame tip.

Figure 7 : Evolution of the thermocouple directly impinged by jet fire and photos showing the consequences of jet fire.



First of all, Figure 7 shows that the temperature of the pipe rises very fast. This is caused by its thermal inertia which is very weak. This weak thermal inertia is due mainly to the thermal diffusivity of the steel which is high and about $1{,}55.10^{-5}$ m²/s. Consequently, in less than one minute, the pipe subjected to the methane fire reaches a thermal equilibrium characterised by an asymptotic temperature of 120 °C. This thermal response is logical since with thermal equilibrium, absorbed heat flux (contributions by radiation and forced convection) and evacuated heat flux (losses by forced convection of water) by the pipe are compensated. It should be noted that this is valid only if absorbed and evacuated heat fluxes remain constant. The pipe impinged by propane and ethylene flame does not reach a thermal equilibrium. Indeed, after having reached a temperature peak, the thermocouple returns a temperature which decreases during time instead of stagnating. The forced convection induced by the water flow remaining unchanged during the test, only a modification of the heat absorbed by the pipe can be at the origin of such a phenomenon. The photographs taken after tests showed that the methane fire had caused an oxidation of steel due to the condensation of the combustion steam coupled with the high temperature in the flame. The formation of this ferric oxide residue did not have any impact on the thermal response of steel. On the other hand, after the propane and ethylene tests, it appeared on the pipe a consequent soot deposit. Thus, we deduced from it that this deposit was at the origin of the temperature decrease. This phenomenon is called "thermophoresis" (Mc Enally, 1997) and corresponds to a laminar transport by which the particles (soot) go upstream a temperature gradient. Indeed, the opaque particles (strongly absorbing) follow usually the heat gradient while escaping from the hot zones to go towards the cold zones. Soot would come to deposit preferentially on the cold pipe and to insulate the pipe thermally as the deposit thickness evolves in the course of time. A test carried out over one forty minutes duration showed that the pipe temperature could go under a temperature of 40°C after having reached a temperature peak of more than 140 °C. The soot particles always remain in place condensing and agglomerating on the pipe in thin layer then in the form of aggregates.

Moreover, this soot deposit plays the same role in the long term as a fireproof material because of a very low thermal conductivity of soot.

CONCLUSION

In order to better characterise the thermal domino effects, which can occur on industrial plants, it is thus necessary to be able to precisely assess the thermal aggression and the thermal response of the impinged equipment.

Accordingly, our experimental research related to the thermal impact of jet fire on a pipe with cooling flow and more particularly, on the part of soot in the heat transfers.

In fact, the important flame radiation is due to soot. The more the flames are concentrated of soot and the more they tend to radiate. Each hydrocarbon has a different propensity to produce soot. For example, the alkenes have a greater disposition than the alkanes. However, in the calculation of the radiative fraction of jet fires (SHELL model), this data is not taken into account. The radiative fraction is an important parameter of the calculation of the thermal consequence-zones. Then, it must be precisely given. The tests carried out within the framework of research program made it possible to clarify this problem of propensity then to test and validate the correlation of Delichatsios based on the theory of the "smoke-point". This correlation permits to determine in a more suitable way the radiative fraction.

If soot generated at high temperature produces an important radiative flux, its settlement on the pipe by a thermophoresis phenomenon tends to thermally insulate the pipe from the external aggression. In accidental conditions, soot as well as a fireproof material would make it possible to protect the equipment and would act like a passive safety barrier. With the difference of the fireproof material, which can worsen in fire, the soot insulating capacity increases during the fire with the growth of its deposit.

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